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Efficient Electricity Portfolios for the United States and Switzerland: An Investor View

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ABSTRACT: This study applies financial portfolio theory to determine efficient electricity-generating technology portfolios for the United States and Switzerland, adopting an investor point of view. Expected returns are defined by the rate of decrease of power generation cost (with external costs included), their volatility, by its standard deviation. The 2003 portfolio contains *Coal*, *Nuclear*, *Gas*, *Oil*, and *Wind* in the case of the United States, and *Nuclear*, *Storage hydro*, *Run of river*, and *Solar* in the case of Switzerland, a country without domestic supplies of fossil fuels. Since shocks in generation costs are found to be correlated, Seemingly Unrelated Regression Estimation (SURE) is used to filter out the systematic component of the covariance matrix of the cost changes. Results suggest that as of 2003, the feasible maximum expected return (MER) electricity portfolio for the United States contains more *Coal*, *Nuclear*, and *Wind* than actual but markedly less *Gas* and *Oil*. By way of contrast, the minimum variance (MV) portfolio combines markedly more *Oil*, *Coal*, *Nuclear*, and *Wind* but almost no *Gas*. Therefore, regardless of the choice between MER and MV, U.S. utilities as investors are substantially inside the efficient frontier. This is even more true of their Swiss counterparts, likely due to continuing regulation of electricity markets.

Keywords: efficiency frontier, energy, electricity, portfolio theory, Seemingly Unrelated Regression Estimation (SURE)

JEL: C32, G11, Q49.

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1 Introduction

Like most industrial countries, the United States and Switzerland face great challenges in the provision of energy arising from increased demand by emerging economies and dwindling domestic resources. The experiences of California in 2001 (and Italy in 2003) demonstrate the high costs of power shortages to the economy. Both the United States and Switzerland are expected to confront substantial shortfalls in the provision of energy during the next twenty years. According to the U.S. National Energy Policy Development Group (NEPG), the projected gap amounts to nearly 50 percent of 2020 demand. Over the next ten years, demand for electricity in particular is predicted to increase by about 25 percent, calling for more than 200,000 MWe of new capacity (NEPG, 2001). As for Switzerland, a study conducted by the Paul Scherrer Institute estimates a power shortfall of almost 20 percent by 2020 given a (slow) demand increase of 15 percent over 2000, and more than 40 percent given a surge in demand of 30 percent (Gantner, 2000).

The solutions available to the two countries is the same, too; viz. import more power (from Canada and France, respectively); improve energy efficiency even more than expected; and increase domestic supply. However, more efficient electricity-generating portfolios could also make a contribution. Can U.S. and Swiss utilities do better as investors by modifying the current technology mix? If so, what are the attractive technologies from an investor's point of view, taking into account external costs that sooner or later will be factored into the prices of energy sources?

Financial investors take great interest in reducing their exposure to the ups and downs of the market by holding a diversified portfolio of securities. Taking into account the variances (standard deviations), covariances, and expected returns between assets, Markowitz (1952) pioneered the construction of the efficient portfolio set. An efficient portfolio does not create unnecessary risk for a given expected return, or put the other way round, it maximizes expected return for a given amount of risk, measured by the standard deviation of portfolio returns.

Indeed, the objectives of the U.S. NEPG support the portfolio approach to energy advocated here. They are "to promote dependable, affordable and environmentally sound production and distribution of energy for the future" (NEPG, 2001). The objectives of energy policy as laid down in the Swiss constitution[1] are to provide energy that should be (i) sufficient, (ii) diversified, (iii) secure, (vi) affordable, and (v) environmentally compatible. To be "dependable", energy must be available in sufficient quality, diversified, and secure; to be "affordable", its provision must be economical. Compatibility with the environment can be achieved by including external costs (which will be done in this study). Again, the portfolio approach appears to be suitable.

A comparison between the United States and Switzerland is of interest for several reasons. First, in spite of the difference in size (the U.S. population is almost 40 times larger than the Swiss), both countries heavily rely on imported fuels (gas and nuclear, respectively) for their power generation. While primary energy sources can be purchased at market prices in both countries, there are differences in their

[1] Section 6, art. 89

technology mix, giving rise to the question of whether they reflect differences in efficiency. Specifically, about 18 percent of total U.S. capacity for electricity was based on gas in 2003, while at present Switzerland has no gas-fueled power plants at all (see Table 1 in section 4.2). In the event that gas should enter its efficient electricity portfolios, Switzerland can learn from the United States. On the other hand, the United States, doing almost without hydro (7 percent of generating capacity in 2003), may benefit from learning about the performance of hydro in Switzerland (some 55 percent[2] of capacity, see panel B of Table 1). Somewhat more general insights may be expected with regard to regulation. Contrary to the United States, the Swiss electricity market continues to be highly regulated. The usual presumption would be that U.S. power generation is closer to the efficient frontier than its Swiss counterpart. The present investigation may allow to test this prediction, thus shedding light on the impact of public regulation in the case of energy. Finally, several countries (notably China and India) have to meet a rapidly increasing demand for electricity. For them, it is of considerable importance to invest in energy sources in a way that avoids inefficiency. This contribution should provide some help towards achieving that objective.

The last-mentioned consideration calls for an investor view. This means that returns are not defined in terms of kilowatthours (kWh) per Dollar spent (which would be appropriate for a current user view), but in terms of relative changes of kWh/$ over time. Accordingly, volatility is measured as the standard deviation of that quantity to determine a risk-expected return tradeoff. Indeed, investment prospects differ between the two countries. Whereas about 90 percent of all new U.S. capacity for power will be fueled by natural gas (NEPG, 2001), in Switzerland gas (much of which comes from Russia) is only slowly being considered as an alternative to nuclear power and electricity imports. Indeed, Russian state-owned Gazprom raised the specter of gauching and squeezing, a behavior that may serve as a model for suppliers of gas worldwide (Economist, 2006).

This paper is structured as follows. Section 2 is devoted to a review of the portfolio approach (Markowitz, 1992) as applied to the provision of energy. While Markowitz theory has been applied to the energy sources of the United States and the European Union before, a recurrent weakness is that estimated variances and covariances (the covariance matrix henceforth), which importantly determine results, may not be stable. Therefore, after specifying U.S. and Swiss efficient electricity production frontiers in section 3, econometric techniques for filtering out the systematic, time-invariant components of the covariance matrix are described in section 4.

The methodological innovation introduced in this study consists in recognizing that there are common shocks impinging on the generation costs of energy sources. Taking this correlation into account in the estimation of the covariance matrix (using so-called Seemingly Unrelated Regression Estimation, SURE) can give rise to important gains in the efficiency of estimation. To the best of the authors' knowledge, SURE has not been applied yet to the calculation of efficient electricity portfolios adopting the investor view. In section 5, SURE-based efficient power generation frontiers are constructed for the United States and Switzerland and contrasted with frontiers derived from Ordinary Least Squares (OLS) estimates. It will be shown that expected returns and volatilities differ greatly depending on the two estimation

[2] *Run of river* and *Storage hydro* combined

procedures. However, even if the SURE-based frontier is accepted as the appropriate one, there remains the open question as to which of the efficient energy mixes is optimal. While optimal choice depends on risk aversion (which is not known), the maximum expected return (MER) and the minimum variance (MV) portfolios constitute two extreme solutions that can be compared with the current portfolios of the two countries. Conclusions are offered in the final section.

2 Review of the literature

Portfolio theory and the concept of diversification have proved useful in areas other than corporate and personal investment. This review of the literature exclusively focuses on applications to energy.

Bar-Lev and Katz (1976) examine fossil fuel procurement to determine the extent to which the U.S. utility industry has been an efficient user of scarce resources. They derive a Markowitz-efficient frontier of fuel mixes which minimize the expected cost of fuels at a given risk (see section 3 on portfolio theory). Their results show that while generally utilities are efficiently diversified, their portfolios are characterized by both high rates of return and excessive risk, with regulation being the likely cause according to the authors. Utilities could move towards the efficient frontier by purchasing higher-priced fuels that exhibit smaller price fluctuations. However, the seminal contribution of Bar-Lev and Katz is limited in several regards. First, it comprises only fuel costs, neglecting other important components such as operating, capital user, and external costs. Fuel is assumed to constitute approximately 80 percent of total generation cost. This assumption may have been legitimate in the early 1970s when electricity was produced mainly by fuel-intensive technologies such as coal, oil, and gas. Today, nuclear, wind, and solar where fuel costs are negligible, play a more important role.

Second, their approach is best described as a current user view, since efficient current operation of a utility calls for choosing the cost-minimizing input bundle. It has been adopted by several later studies, most notably by Adegbulugbe et al. (1989), Roques et al. (2005, 2006), Doherty et al. (2005), Grubb et al. (2005), Jansen et al. (2006), and Krey and Zweifel (2008). However, utilities make a choice of technology often involving an upfront investment that promises a stream of future revenues and costs. They are thus in a position of an investor who – while not irreversibly tied to a set of assets – expects to hold a given portfolio for a few years. The appropriate view in that case is that of an investor who is concerned about changes in value over time, viz. the percentage reduction of unit cost associated with a generating technology. Indeed, this contribution is one of the first to adopt this investor view, which is actually predicated by portfolio theory, following the lead of Humphreys and McClain (1998).

A third limitation of the study by Bar-Lev and Katz is that it fails to take into account the fact that the covariance matrix of primary energy prices (and their relative changes over time) are likely to vary over time. This problem was also addressed by Humphreys and McClain, who introduced a time-varying covariance matrix in their construction of an efficient portfolio of U.S. energy sources. Estimated variances and covariances are derived from so-called Generalized Autoregressive Conditional Heteroscedastic (henceforth: GARCH) models. GARCH modelling allows to filter out systematic changes in volatility in response to shocks. Without filtering, these shocks may result in unstable estimates of the covariance matrix. The authors find that while the electric utility industry is operating close to the minimum variance (MV) portfolio, a shift towards coal would still reduce overall price volatility at a given rate of return. With the inclusion of expected external costs, the shift away from oil, while confirmed, now favors natural gas rather than coal. Humphreys and McClain also present evidence suggesting that changes in generation costs are characterized by skewness and excess kurtosis, implying that conditional densities likely are not normal. However, under these conditions GARCH does not provide useful inferences and should be replaced by an alternative approach. In addition, their study is limited to fuel price and environmental externality surcharges excluding operating and capital user costs. With a broader range of technologies considered, it becomes increasingly important to account for possible correlations between unobserved shocks impinging on the unit cost of generating technologies to achieve efficiency gains [applying Seemingly Unrelated Regression Estimation (SURE)] in estimation. The present study promises advances on these scores as well.

Yu (2003) presents a short-term market risk model again based on the Markowitz mean-variance approach, where the covariance matrix reflects differing developments of fuel prices across regional electricity markets. He includes transaction costs and other constraints such as minimum contracting quantities that limit wheeling, resulting in a mixed-integer programming problem. An interesting observation is that the resulting efficient frontier is neither smooth nor concave from below anymore, contrary to the illustration of Figure 1 in section 3 below.

However, Yu does not control for non-normal conditional densities, which easily lead to biased regression estimates that result in faulty predictions of future price changes. In addition, the study continues to neglect possible correlations between unobserved shocks impinging on prices. Such correlations should be of great concern in his study since it uses data from regions in the United States, which may be subject to common shocks (notably weather, as evidenced by the electricity price hikes in California that were mainly caused by dry and hot weather in the states of Washington, Utah, Nevada, and Arizona (Cicchetti et al., 2004, Ch. 18)).

Being strong advocates of the investor view, Berger et al. (2003) analyze existing and projected generating portfolios in the European Union (EU), comparing existing risk-return properties to a set of Markowitz-efficient portfolios. In general, their results indicate that both existing and projected EU technology mixes are suboptimal from a risk-return perspective. Their analysis further suggests that portfolios with lower cost increases and less risk can be attained by including greater amounts of renewables (which typically have high fixed but low variable costs, such as wind).

However, the study by Berger et al. does not take account of external costs, likely biasing results somewhat in favor of fossil fuels (but see the qualification in section 4.2 below). Also, their return and risk estimates are derived using financial proxies. For example, fixed and variable costs of operation and management (O&M) are approximated by using historical business data such as the S&P 500 index, the Morgan Stanley MCSI Europe index, and treasury bills. Finally, the report does not publish results of commonly known statistical tests showing whether their proxies do correlate with endogenous variables (using e.g. Shea's partial *r*-squared test, or *F*-tests for excluded instruments), and whether they are orthogonal to disturbance terms (Sargan test). There is strong support in the econometric literature of the view that weak proxies result in unreliable estimates (Greene, 2003, ch. 5). As is true of the other studies, Berger et al. fail to consider correlations of unobserved shocks impinging on generation costs.

Summing up this review, using a more comprehensive set of technologies, more comprehensive cost data, and refined econometric methodology appears to be a promising approach to obtain improved efficient frontiers for electricity-generating energy portfolios.

3 Portfolio theory

Rational holders of a portfolio of assets seek to maximize its expected return at a given level of risk or alternatively to minimize risk given a certain expected return. In the present context, the portfolio consists of generating technologies. Its expected return depends on the expected returns of the individual technologies, weighted by their share, with returns measured by the percentage change in U.S. cents/kWh of power generated. This definition is similar to that of Berger (2003) and Awerbuch and Berger (2003).

The expected return on a portfolio $E(\mathrm{R}_p)$ consisting of *m* technologies is thus given by

$$E(\mathrm{R}_p) = \sum_{i=1}^{m} w_i E(\mathrm{R}_i), \quad \text{with } \sum_{i=1}^{m} w_i = 1, \tag{1}$$

where $E(\mathrm{R}_i)$ is the expected return (percentage change of U.S. cents/kWh) of technology *i* and w_i is the share (weight) of technology *i* in the portfolio. For example, the 2003 portfolio for the United States consists of five electricity assets, viz. *Coal*, *Nuclear*, *Gas*, *Oil*, and *Wind* (as described in section 4.2 below). Therefore,

$$E(\mathrm{R}_p, US2003) = w_1 E(\mathrm{R}_1) + w_2 E(\mathrm{R}_2) + w_3 E(\mathrm{R}_3) + w_4 E(\mathrm{R}_4) + w_5 E(\mathrm{R}_5). \tag{2}$$

The volatility of the portfolio's expected return involves not only the respective variances but all the covariances as well. Therefore, one has for the standard error of portfolio returns σ_p,

$$\sigma_p(US2003) = \sqrt{\begin{aligned} & w_1^2\sigma_1^2 + w_2^2\sigma_2^2 + w_3^2\sigma_3^2 + w_4^2\sigma_4^2 + w_5^2\sigma_5^2 + 2w_1w_2\rho_{12}\sigma_1\sigma_2 \\ & + 2w_1w_3\rho_{13}\sigma_1\sigma_3 + 2w_1w_4\rho_{14}\sigma_1\sigma_4 + 2w_1w_5\rho_{15}\sigma_1\sigma_5 + 2w_2w_3\rho_{23}\sigma_2\sigma_3 \\ & + 2w_2w_4\rho_{24}\sigma_2\sigma_4 + 2w_2w_5\rho_{25}\sigma_2\sigma_5 + 2w_3w_4\rho_{34}\sigma_3\sigma_4 + 2w_3w_5\rho_{35}\sigma_3\sigma_5 \\ & + 2w_4w_5\rho_{45}\sigma_4\sigma_5 \end{aligned}}, \tag{3}$$

where $\rho_{i,j} = \mathrm{cov}_{i,j}/(\sigma_i\sigma_j)$, $i,j = 1,\ldots,5$, are correlation coefficients, and σ_i, the standard error of technology *i*'s returns.

The set of efficient portfolios is the solution of two equivalent problems,

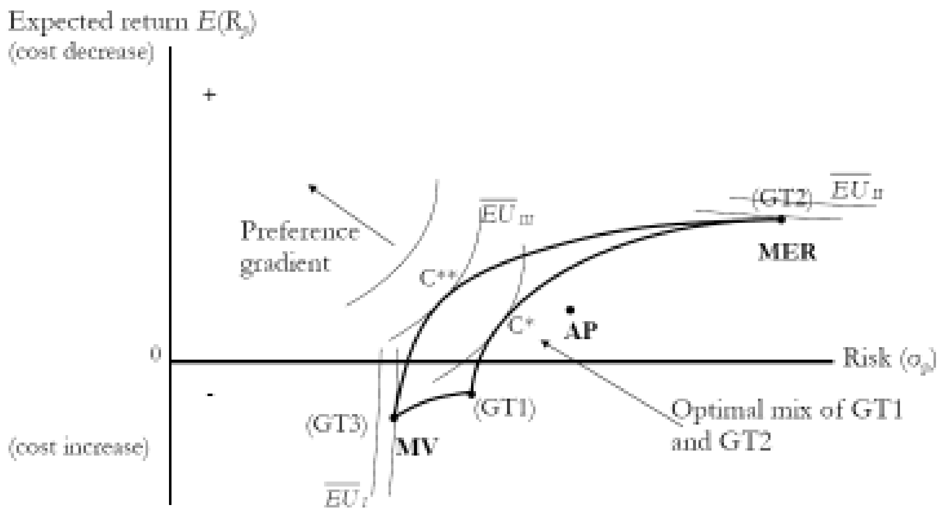
$$\max_{w_i} E(R_p) \text{ s.t.} \sum w_i = 1, \sigma \leq \overline{\sigma}, \tag{4}$$

$$\min_{w_i} \sigma_p \text{ s.t.} \sum w_i = 1, E(R_p) \geq \overline{R}. \tag{5}$$

The first formulation says that the expected return of the portfolio is to be maximized subject to the constraint that volatility must not exceed a limit value $\overline{\sigma}$. The second formulation says that volatility shall be minimized, without however having expected return fall below a limit value $\overline{R}$. In both cases, the decision variables are the shares w_i assigned to the components of the portfolio, i.e. the generating technologies in the present context. As for Switzerland, the 2003 portfolio contains four assets, viz. *Nuclear*, *Storage hydro*, *Run of river*, and *Solar* (see section 4.2 again for details). Equations (2) and (3) are modified accordingly.

Figure 1 illustrates the case of two generating technologies (initially; later, a third will be added). The horizontal axis depicts risk as measured by the standard deviation σ_p, while the vertical axis displays the expected return $E(R_p)$, defined in analogy to eqs. (2) and (3), respectively. For an investor, the positive segment of the vertical axis reflects the case where the costs of generation technologies are falling, causing expected returns to be positive.

Figure 1: Efficient portfolios of generation technologies (GT)



By assumption, let generating technology GT1 have increasing generation cost (e.g. *Run or river* in the case of Switzerland). By way of contrast, let GT2 be more risky but have positive expected returns because its cost tend to fall (e.g. *Storage hydro*). Due to the correlation terms contained in equation (3), the efficient frontier linking GT1 and GT2 (i.e. combining the two technologies) is not linear but part of an ellipse. Thus, if the correlation between two electricity generation technologies is less than perfect ($-1 < \rho_{12} < 1$), the efficient frontier between GT1 and GT2 runs concave from below. The lower the correlation coefficient, the stronger this portfolio effect. However, the choice of the optimal among the efficient portfolios depends on the preferences of the investor. Figure 1 exhibits three types, extremely risk averse (I), almost risk neutral (II), and moderately risk averse (III). Along an indifference curve, expected utility (EU) is held constant. The more the preference gradient points towards the $E(R_p)$ and away from the σ_p axis, the more marked is the investor's risk aversion. Thus, for the intermediate type III, the solution C* is optimal. However, an actual portfolio given by point AP would be inefficient regardless of risk preferences, lying inside the efficient frontier. Note that if returns of GT1 and GT2 move in a perfectly opposite way ($\varrho_{12} = -1$), then a portfolio with no volatility at all can be constructed (Ingersoll, 1987, ch. 4). Such a portfolio always yields the same expected return, since whenever returns of GT2 are higher than expected, returns of GT1 are below expectation by an equal amount.

Now let there be a third technology (GT3). This creates additional opportunities for diversification, shifting the efficient frontier upward and inward. As before, knowledge of investors risk preferences would be necessary to predict their choices of portfolio. While this knowledge is lacking with regard to U.S. and Swiss utilities, two extreme solutions are worth pointing out. As can be gleaned from Figure 1, a very risk-averse investor (type I) is predicted to opt for the minimum variance (MV) portfolio. By way of contrast, an (almost) risk-neutral utility (type II) prefers the maximum expected return (MER) portfolio, usually implying a very different mix of generating technologies (see section 5.2 below). Comparing these two extreme solutions permits to assess the maximum influence of risk aversion on the optimal portfolio of power generation technologies.

Note that this approach does not revolve around single technologies, but an efficient mix of several technologies. Even if a particular technology appears dominant, less promising technologies (featuring low expected returns and/or high risk) may still contribute to the portfolio because of their diversification effect [see the impact of low or even negative correlation coefficients in eq. (3)].

4 Econometric analysis

The objective of this section is to construct a correlation matrix of returns that purges the observations from singular shocks while retrieving as much information from the data possible. To this end, observed unit cost changes will be related to a set of explanatory variables using Seemingly Unrelated Regression Estimation (SURE).

4.1 Seemingly Unrelated Regression Estimation (SURE)

Expected rates of return pertaining to technologies [$E(R_i)$ in eq. (1)] could in principle be estimated equation by equation using Ordinary Least Squares (OLS). However, if there are unobserved common shocks impinging on technologies at the same time, the error terms $\varepsilon_{i,t}$ are correlated across equations. This constitutes information that can be used to obtain sharper estimates of the β parameters in the following regression,

$$R_{i,t} = \beta_{i0} + \sum_{j=1}^{m} \beta_{i,j} \cdot R_{i,t-j} + \varepsilon_{i,t}, \tag{6}$$

where $R_{i,t}$ is the percentage change in generation cost (inverse of returns) of technology *i* in year *t*, β_{i0} is a constant for technology *i* indicating a positive drift, $\beta_{i,j}$ is the coefficient pertaining to the returns lagged *k* years, $R_{i,t-j}$ is the dependent variable lagged *k* years, and $\varepsilon_{i,t}$ is the error term pertaining to technology *i* in year *t*. Where appropriate this autoregressive equation is augmented by a time trend ($Trend_{i,t}$).

While this formulation suffices to insulate expected conditional values $\hat{R}_{i,t}$ from extreme shocks (which would spill over into the estimated correlation matrix), SURE holds the promise of achieving this aim in a particular way, benefitting from the fact that the error terms are correlated across equations (see section 5.1.2 for empirical evidence).

In the present context, the SURE model consists of *q* regression equations (*q* being the number of electricity-generating technologies), each of which satisfies the assumptions of the standard regression model. Model (7) displays the set of equations that make up SURE of the U.S. portfolio for 2003 (coefficients are postmultiplied to prepare for the matrix notation introduced below),

$$\begin{aligned}
R_{Coal,03} &= c_0 + R_{Coal,02}c_1 + Trend_t c_2 + \varepsilon_{Coal,03} \\
R_{Nucl,03} &= n_0 + R_{Nucl,02}n_1 + Trend_t n_2 + \varepsilon_{Nucl,03} \\
R_{Gas,03} &= g_0 + R_{Gas,02}g_1 + R_{Gas,01}g_2 + R_{Gas,00}g_3 + Trend_t g_4 + \varepsilon_{Gas,03} \\
R_{Oil,03} &= b_0 + R_{Oil,02}o_1 + R_{Oil,01}o_2 + R_{Oil,00}o_3 + R_{Oil,99}o_4 + R_{Oil,98}o_5 \\
&\quad + Trend_t o_6 + \varepsilon_{Oil,03} \\
R_{Wind,03} &= d_0 + R_{Wind,02}d_1 + Trend_t d_2 + \varepsilon_{Wind,03}.
\end{aligned} \tag{7}$$

Generally, influences such as technological change, increases and decreases in the cost of inputs used in the production of the technology considered, and natural disasters are hypothesized to influence unit costs of electricity generation and hence returns. However, estimating such a comprehensive model is beyond the scope of this study. Rather, the relative cost change of nuclear energy in the United States in the year 2003 e.g., $R_{Nucl,03}$, is related to a constant (n_0), the cost change in the preceding year $R_{Nucl,02}$, and a time trend ($Trend_t$).

In analogy, the cost change of nuclear energy in Switzerland in the year 2003, $R_{Nucl,03}$, is related to a constant (n'_0), the cost changes in the preceding years $R_{Nucl,02}$, $R_{Nucl,01}$, $R_{Nucl,00}$, and $R_{Nucl,99}$, and a time trend $(Trend'_t)$. The other equations relate to *Run of river* (*Ror*), *Storage hydro* (*Sh*), and *Solar* (*Solar*, which also includes other renewable energy sources such as waste),

$$
\begin{aligned}
R_{Nucl,03} &= n'_0 + R_{Nucl,02}n'_1 + R_{Nucl,01}n'_2 + R_{Nucl,00}n'_3 + R_{Nucl,99}n'_4 + Trend_t n'_5 + \varepsilon'_{Nucl,03} \\
R_{Ror,03} &= r'_0 + R_{Ror,02}r'_1 + Trend_t r'_2 + \varepsilon'_{Ror,03} \\
R_{Sb,03} &= b'_0 + R_{Sb,02}b'_1 + Trend_t b'_2 + \varepsilon'_{Sb,03} \\
R_{Solar,03} &= s'_0 + R_{Solar,02}s'_1 + R_{Solar,01}s'_2 + R_{Solar,00}s'_3 + R_{Solar,99}s'_4 + Trend_t s'_5 + \varepsilon'_{Solar,03}.
\end{aligned}
\tag{8}
$$

As for $\varepsilon_{i,t}$, the t_{th} element of ε_i, we assume that the $(\varepsilon_{1,t}, \varepsilon_{2,t}, ..., \varepsilon_{q,t})$ are iid, with $E(\varepsilon_{i,t}) = 0$ and $E(\varepsilon_{i,t}\varepsilon_{j,s}) = \sigma_{i,j}$ if $t = s$ and $= 0$ if $t \neq s$. This is the SURE specification, admitting nonzero contemporaneous correlations between error terms. Written in matrix algebra, the system (7)[3] reads,

$$
\begin{bmatrix} R_{Coal,03} \\ R_{Nucl,03} \\ R_{Gas,03} \\ R_{Oil,03} \\ R_{Wind,03} \end{bmatrix} = \begin{bmatrix} X_{Coal} & 0 & 0 & 0 & 0 \\ 0 & X_{Nuclear} & 0 & 0 & 0 \\ 0 & 0 & X_{Gas} & 0 & 0 \\ 0 & 0 & 0 & X_{Oil} & 0 \\ 0 & 0 & 0 & 0 & X_{Wind} \end{bmatrix} \cdot \begin{bmatrix} c_{Coal,03} \\ n_{Nucl,03} \\ g_{Gas,03} \\ o_{Oil,03} \\ d_{Wind,03} \end{bmatrix} + \begin{bmatrix} \varepsilon_{Coal,03} \\ \varepsilon_{Nucl,03} \\ \varepsilon_{Gas,03} \\ \varepsilon_{Oil,03} \\ \varepsilon_{Wind,03} \end{bmatrix}; \tag{9}
$$

where e.g.

$X_{Oil} = [1 \;\; R_{Oil,02} \;\; R_{Oil,01} \;\; R_{Oil,00} \;\; R_{Oil,99} \;\; R_{Oil,98} \;\; Trend_t]$ and

$b_{Oil,03} = [o_0 \; o_1 \; o_2 \; o_3 \; o_4 \; o_5 \; o_5]'$.

All other variables are defined analogously. The regressor matrix on the right-hand side is block diagonal, indicating that e.g. the cost change in the nuclear technology of 2003 is only related to its own history but not to cost changes in the other technologies. These *k* equations (involving *T* observations each) can be presented as a system by using **X** as the symbol of the block diagonal matrix in system (9),

$$
\mathbf{R} = \mathbf{Xb} + \mathbf{e}, \qquad E(\mathbf{ee'}) = \mathbf{\Omega}. \tag{10}
$$

The assumption that is specific to SURE is that the covariance matrix of error terms is not diagonal,

$$
\mathbf{\Omega} = E(\mathbf{ee'}) = \begin{bmatrix} \sigma_{CoalCoal}I & \sigma_{CoalNucl}I & \sigma_{CoalGas}I & \sigma_{CoalOil}I & \sigma_{CoalWind}I \\ \sigma_{NuclCoal}I & \sigma_{NuclNucl}I & \sigma_{NuclGas}I & \sigma_{NuclOil}I & \sigma_{NuclWind}I \\ \sigma_{GasCoal}I & \sigma_{GasNucl}I & \sigma_{GasGas}I & \sigma_{GasOil}I & \sigma_{GasWind}I \\ \sigma_{OilCoal}I & \sigma_{OilNucl}I & \sigma_{OilGas}I & \sigma_{OilOil}I & \sigma_{OilWind}I \\ \sigma_{WindCoal}I & \sigma_{WindNucl}I & \sigma_{WindGas}I & \sigma_{WindOil}I & \sigma_{WindWind}I \end{bmatrix}. \tag{11}
$$

[3] The equation system for Switzerland can be constructed in the same way but for brevity is not shown.

The seemingly unrelated regression (SURE) model therefore allows to simultaneously estimate the expected returns of all power generation technologies in one regression, taking into account possible correlations of error terms across equations.

4.2 The data

The U.S. data set consists of five variables; *Coal*, *Nuclear*, *Gas*, *Oil*, and *Wind* power[4], covering the years 1982 to 2003. All variables are annual cost changes in U.S. cents per kWh electricity (inverse of expected returns), deflated by CPI, with 2000 serving as the base year (=100)[5]. The Swiss data on *Nuclear*[6] covers the years 1986 to 2003, those on *Run of river*[7] and *Storage hydro*[8] 1993 to 2003, and *Solar*[9], 1991 to 2003. Only aggregated data were available, masking regional variations in generating costs. However, the data do represent more than 50 percent of national production capacity in both countries. Throughout, generation costs comprise (i) fuel costs, (ii) costs of current operations, and (iii) capital user cost[10] (depreciation of book value plus interest). In the case of *Nuclear*, decommissioning and waste disposal are also included. An externality surcharge for environmental damage caused by power generation is added on top of each cost variable. These cost data are available for total production only, precluding a differentiation according to load segments, which seems to have been a problem with previous studies as well (Awerbuch 2006, 2005, 2003).

From society's point of view, the price of a product should reflect external costs to the extent that the marginal benefit of internalization effort still covers its marginal cost. This means that full internalization almost always entails an efficiency loss because in that event, expected marginal benefit necessarily is zero, while the marginal cost of internalization effort is substantial (e.g., filtering out the last 0.1 percent of toxic substances contained in a body of water causes very high cost). No external cost data for the United States were available; therefore data from the United Kingdom were used (European Commission, 2003). They serve as a good proxy because the UK generation mix and structure of the electricity industry are similar to that of the United States. Externality surcharges for Switzerland are taken from Hirschberg (1999), who implicitly assumes 100 percent internalization when dividing estimated total external cost by total final energy produced by the technology considered. Swiss and UK external cost data are comparable, both being generated by the same methods. While external costs related to health and global warming do enter

[4] Data for *Coal*, *Nuclear*, *Gas* and *Oil* were obtained from the UIC (2005). *Wind* (State Hawaii, USA (www.state.hi.us) and U.S. Department of Energy (www.energy.gov)). Since the *Wind* data was not available for every year, values for 1983, 1985-1987, 1989-1994, 1996-1999 were generated by cubic spline interpolation (Knott, 2000).

[5] The mean value of the exchange rate for the year 2000 was used to convert Swiss cents into U.S. cents, as published by the U.S. Federal Reserve (http://research.stlouisfed.org). Deflation is appropriate because contrary to financial investors, utilities need to adopt a long planning horizon in view of the lags involved in the construction of new plants

[6] Data sources: KKL (2005), KKG (2005)

[7] Data source: personal correspondence

[8] Data source: personal correspondence

[9] RWE (2005); The average exchange rate of 2000 was used to convert Euro cents into U.S. cents (source: U.S. Federal Reserve). RWE data from Germany is used as a proxy for Swiss solar electricity data, since solar generation technologies in both countries are similar.

[10] Capital user cost can be defined in several ways. The variant "linear depreciation and interest" is used here exclusively due to lack of source data, that would permit to calculate other variants.

calculations, no data are available for some other categories such as external costs related to agriculture and forestry. In this paper, the upper bound of social cost estimates is adopted for both countries (Hirschberg, 1999; EC, 2003).

The results of these calculations are displayed in Table 1. As noted in the Introduction section, U.S. power generation is dominated by *Coal* (panel A). However, with externality surcharges included, *Coal* cost some 9 U.S. cents (busbar) in 2003, while *Wind* power was amongst the low-cost sources.

Table 1: Shares in generation (percent) and cost levels (U.S. cents/kWh, prices of 2000)

Panel A: United States[*)]

Technology	Shares		1995	2003
	1995	2003		
Coal	57	56	11.44	8.99
Nuclear	21	21	5.77	3.80
Gas	17	18	6.20	7.56
Oil	3	3	11.27	10.10
Wind	2	2	5.44	4.35

[*)] Excluding hydro (see section 4.3)

Panel B: Switzerland

Technology	Shares		1995	2003
	1995	2003		
Nuclear	39	40	4.97	3.47
Storage hydro	27	32	2.59	1.91
Run of river	32	24	5.69	4.04
Solar	2	4	80.76	47.41

Sources: SFOE (2004), IEA (2005)

Three of the four Swiss generation technologies are comparable to those of the United States in terms of unit cost, being in the 2 to 4 U.S. cents/kWh (busbar) range in 2003 (see panel B of Table 1). By way of contrast, *Solar* was several magnitudes more expensive both in 1995 and 2003.

However, note that cost levels are not relevant for investors in the capital market, who are not concerned about the price of a share. An expensive share that has the potential to still go up in the future can be part of an efficient portfolio. In full analogy, a utility, acting as an investor, would have wanted to buy into Swiss *Solar* in 1995 regardless of its initial unit cost because of the rapid decrease in the course of nine years. From an investor point of view, Swiss *Solar* should therefore figure prominently in an efficient portfolio unless it has extremely unfavorable diversification properties.

Utilities do adopt a current user view when deciding e.g. whether to buy more or less gas for fueling existing plant. However, when the choice of a technology is involved, the investor rather than the current user view is appropriate. Thus this paper seeks to answer the question, How should utilities (and policy makers) have started restructuring the electricity generating portfolio in the 1980s (assuming they knew the cost changes occurring until 2003) in order to arrive at the MER or the MV portfolio by 2003, depending on their risk preferences?

4.3 Current U.S. and Swiss generation portfolios

To establish the respective benchmarks, the actual electricity portfolios of the United States and Switzerland (as of 2003) are presented in this section. As shown by panel A of Table 1 again, the U.S. mix predominantly consists of fossil fuels (56 percent *Coal,* 21 percent *Nuclear*, 18 percent *Gas*, and 3 percent

Oil), with *Nuclear* accounting for another 21 percent of production. *Wind* is negligible. These shares are overestimates because no data was available for hydro power, which contributed an estimated 6 to 10 percent to total U.S. power generation between 1995 to 2003. Nevertheless, more than 90 percent of U.S. capacity is covered in this analysis, going beyond earlier work that was limited to three technologies (Awerbuch, 2006; Humphreys and McClain, 1998). The actual (2003) Swiss portfolio relies heavily on hydro (32 percent *Storage hydro*, 24 percent *Run of river*); *Nuclear* accounts for 40 percent, *Solar* (a proxy of all renewable and conventional thermic technologies), for a mere 4 percent (panel B of Table 1). Here, the data cover more than 90 percent of capacity.

5 Efficient frontiers for U.S. and Swiss power generation

5.1 Time series analysis

5.1.1 Preliminary testing

The objective is to obtain a stable estimate of the covariance matrix $\mathbf{\Omega}$ of equation (10). In order to be able to filter out the systematic (trend stable) component of $\mathbf{\Omega}$, changes in generation cost must form stationary time series. Given nonstationarity, the estimate of $\mathbf{\Omega}$ would shift over time, precluding the estimation of a reasonably stable efficient frontier [Wooldridge (2003), ch. 11].

To test for stationarity the augmented Dickey-Fuller (ADF) test was applied. Results indicate at the one percent significance level that all cost changes in the U.S. and Swiss data sets are stationary. To determine the correct lag order for the SURE regressions, several tests were applied, viz. Akaike's information criterion (AIC), Hannan & Quinn’s information criterion (HQIC), Schwartz's Bayesian information criterion (SBIC), and the likelihood ratio test (LR) (Al-Subaihi, 2002; Liew, 2004). The results for the U.S. data suggest five lags for *Oil*, three lags for *Gas*, and one lag for *Coal*. One lag was used for *Wind* and *Nuclear*, based on considerations of goodness of fit in SURE (see Table 4). The results for the Swiss data suggest four lags for *Nuclear*, while in the case of *Storage hydro* and *Run of river*, one lag suffices (see Appendix, Table A1). Tests are inconclusive for *Solar*.

However, Liew (2004) shows that lag selection tests may lack validity if the sample is small. Using a sample size of 25 he finds that the probability of correctly estimating the true order of an autoregressive process ranges between 58 percent (SBIC) and 60 percent (HQIC). In view of the inconclusive evidence and the fact that the coefficients on the autoregressive variables used in the SURE procedure are significant without exception, four lags were applied throughout in the case of Swiss for *Solar*.

5.1.2 Seemingly Unrelated Regression Estimation (SURE) results

Having established the specification of the different equations, the possible presence of correlations across equations can be tested for. Panel A of Table 2 does indicate some negative correlations in the SURE residuals for the United States, with that between *Wind* and *Coal* attaining a value of -0.4246. Panel B of Table 2 tests whether OLS residuals would also have suggested SURE. While the estimated correlation coefficient for *Wind* and *Coal* would have been similar with –0.4062, correlation coefficients between *Nuclear* and *Coal* are less marked than their SURE counterparts. A striking difference can be seen in the case of *Gas* and *Wind*. The correlation in the SURE residuals is positive, while that between OLS residuals is negative.

Table 2: Correlation matrices for the United States

Panel A: Partial correlation coefficients for $\hat{\varepsilon}_{i,t}$ residuals from system (9), (1982-2003) using SURE

	Coal	*Nuclear*	*Gas*	*Oil*	*Wind*
Coal	1				
Nuclear	-0.1140	1			
Gas	0.7605	0.0113	1		
Oil	-0.3317	0.4461	-0.2621	1	
Wind	-0.4246	-0.2520	0.1150	-0.1492	1

Panel B: Partial correlation coefficients for $\hat{\varepsilon}_{i,t}$ residuals from equation (6), (1982-2003) using OLS

	Coal	*Nuclear*	*Gas*	*Oil*	*Wind*
Coal	1				
Nuclear	-0.0329	1			
Gas	0.7050	-0.0004	1		
Oil	-0.2835	0.3670	-0.1362	1	
Wind	-0.4062	-0.1644	-0.2073	0.0998	1

Table 3: Correlation matrices for Switzerland

Panel A: Partial correlation coefficients for $\hat{\varepsilon}_{i,t}$ residuals from system (9), (1986-2003) using SURE

	Nuclear	*Storage hydro*	*Run of river*	*Solar*
Nuclear	1			
Storage hydro	-0.4644	1		
Run of river	-0.2685	0.5054	1	
Solar	0.5933	0.0367	-0.5907	1

Panel B: Partial correlation coefficients for $\hat{\varepsilon}_{i,t}$ residuals from equation (6), (1986-2003) using OLS

	Nuclear	*Storage hydro*	*Run of river*	*Solar*
Nuclear	1			
Storage hydro	0.3111	1		
Run of river	-0.0550	0.5066	1	
Solar	0.7201	0.2056	-0.3824	1

In the case of Switzerland (Table 3), the highest partial correlation coefficient between SURE residuals (Panel A) is obtained for *Solar* and *Nuclear* (0.5933), followed by *Run of river* and *Storage hydro* (0.5054). In the latter case, the common unobserved shock clearly is weather conditions, in particular the amount of precipitation. The pertinent correlation coefficient between OLS residuals (Panel B) is somewhat larger with 0.7201 for *Solar* and *Nuclear* and about the same for *Run of river* and *Storage hydro* with 0.5066.

Table 4: Results of SURE regressions, United States (1982-2003)

	$\overline{R}$	St.D.	Const.	R_{t-1}	R_{t-2}	R_{t-3}	R_{t-4}	R_{t-5}	Trend	Obs	R^2
Coal	5.2	2.0	-0.09***	0.02					0.003***	17	0.67
Nuclear	5.8	1.8	-0.05*	0.38**					0.001	17	0.07
Gas	3.9	11.7	-0.32***	0.10	-0.89***	0.12			0.018***	17	0.67
Oil	2.5	10.4	-1.05***	-0.96***	-1.35***	-1.17***	-1.21***	-0.622**	0.050***	17	0.67
Wind	5.4	6.9	-0.03	0.73***					0.001	17	0.51

*** significant at 1 percent level, ** significant at 5 percent level, * significant at 10 percent level

The SURE and OLS regressions underlying these calculations are displayed in Tables 4 and 5 for the United States (for Switzerland, see Appendix). The contrasts are sometimes striking. Notably, the SURE results of Table 4 (col. ***"Const."***) suggest a cost-increasing drift of 5 percent p.a.[11] in *Nuclear*, while according to the OLS estimate of Table 5, the hypothesis of no drift cannot be rejected. In the case of *Wind*, it is the other way round.

Table 5: Results of OLS regressions, United States (1982-2003)

	$\overline{R}$	St.D.	Const.	R_{t-1}	R_{t-2}	R_{t-3}	R_{t-4}	R_{t-5}	Trend	Obs	R^2
Coal	4.8	1.5	-0.06***	0.22***					0.002**	21	0.36
Nuclear	4.8	2.3	-0.01	0.30					-0.002	21	0.21
Gas	3.6	10.5	-0.26**	0.13	-0.78***	0.23			0.015**	19	0.69
Oil	2.5	9.7	-0.91**	-0.85**	-1.21***	-0.94*	-1.10**	-0.43	0.043**	17	0.62
Wind	4.1	2.6	-0.05**	0.21**					0.002	21	0.72

*** significant at 1 percent level, ** significant at 5 percent level, * significant at 10 percent level

In the Swiss regressions (see Appendix, Tables A1 and A2), *Solar* exhibits the expected downward cost shift in the SURE estimation, which would have not been recognized as significant in the OLS alternative. On the whole, the SURE results are quite satisfactory and are preferred since they use more information than their OLS counterparts, taking into account correlations in unobserved shocks.

5.2 Construction of efficient electricity portfolios

In this section, theory and data are combined for the construction of efficient portfolios of electricity-generating technologies, or efficient electricity portfolios for short. The theory for this is given by

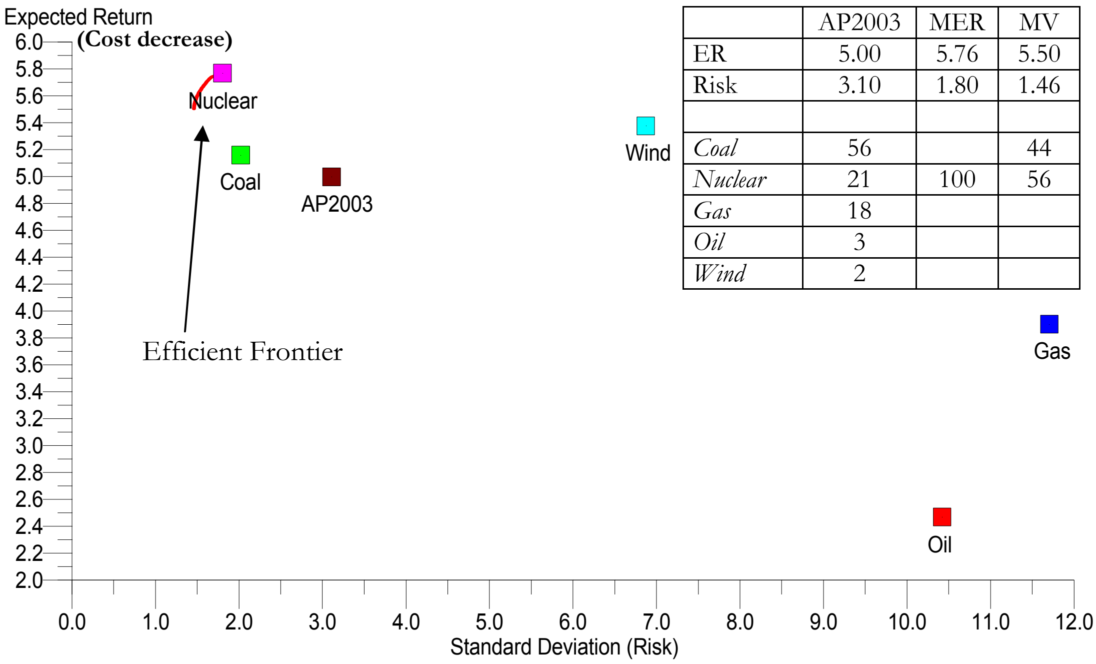
[11] A positive value indicates a cost decrease, a negative value a cost increase (see Figure 1).

equations (2) and (3). It calls for an estimate of expected returns $E(R_i)$ for each technology i that potentially is part of the efficient portfolio, of its standard error σ_i, and its covariances σ_{ij}. Estimates of these quantities come from the SURE results shown in Table 4 (for the United States) and Table A1 in the Appendix (for Switzerland). The expected rate of return of the efficient portfolio $E(R_p)$ as well as the shares of the technologies entering that portfolio can be calculated for an arbitrary year t. In the following, only efficient frontiers for t = 2003 will be derived, defining the current efficient portfolios.

5.2.1 Current (2003) efficient electricity portfolios for the United States

Figure 2 displays the efficiency frontier for the United States without any constraints. If utilities' sole interest were to maximize expected return (thus maximizing the expected decrease of power generation costs), they would choose the MER (maximum expected return) portfolio, which contains *Nuclear* exclusively. If they wish to minimize risk, opting for the MV (minimum variance) portfolio, then a mix of 56 percent *Nuclear* and 44 percent *Coal* would be optimal.

Figure 2: Efficient Electricity Portfolios for the United States
(2003, SURE-based, no constraints)



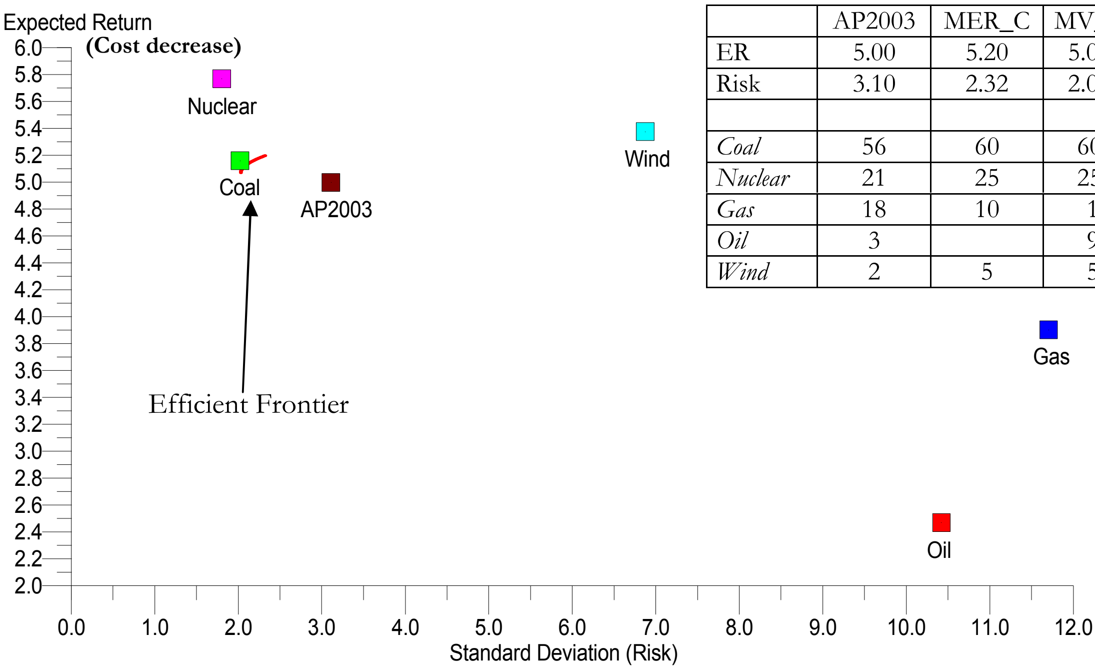
	AP2003	MER	MV
ER	5.00	5.76	5.50
Risk	3.10	1.80	1.46
Coal	56		44
Nuclear	21	100	56
Gas	18		
Oil	3		
Wind	2		

Therefore, the degree of risk aversion characterizing U.S. utilities clearly matters. However, risk aversion has its price because opting for MV rather than MER would entail a cost reduction of 5.5 rather than 5.76 percent p.a. Still, the MV portfolio with its annual volatility of 1.46 percent beats the actual one whose cost reduction is 5 percent only, associated with an annual volatility of 3.10 percent.

Yet a share of *Nuclear* amounting to 100 rather than 21 percent in the MER portfolio (or 56 rather than 21 percent in the MV portfolio) must be deemed unrealistic for the United States of 2003. Therefore,

Figure 3 shows an efficient frontier that takes into account that the current portfolio could be adjusted at considerable cost only. Since adjustment costs are unknown, upper limits are imposed on the individual shares for simplicity to reflect technical feasibility. For example, the share of *Wind* cannot exceed 5 percent by assumption (see insert below Figure 3).

Figure 3: Efficient Electricity Portfolios for the United States
(2003, SURE-based, with constraints)



	AP2003	MER_C	MV_C
ER	5.00	5.20	5.07
Risk	3.10	2.32	2.03
Coal	56	60	60
Nuclear	21	25	25
Gas	18	10	1
Oil	3		9
Wind	2	5	5

Constraints imposed:
Coal ≤ 60%, *Nuclear* ≤ 25%, *Oil* ≤ 10%, *Wind* ≤ 5%

In the MER_C (with "C" for constrained) portfolio, the generation mix now contains 60 percent *Coal*, 25 percent *Nuclear*, 10 percent *Gas*, and 5 percent *Wind*, indicating that this last constraint is binding. Compared to the actual portfolio, the cost decrease would still speed up (from 5.00 percent p.a. to 5.20 percent p.a.), while volatility would be reduced from 3.10 to 2.32 percent p.a.

In the MV_C alternative, the highest share is again allocated to *Coal* (60 percent, binding [12], up from 56 percent in the actual portfolio), followed by *Nuclear* (25 percent, binding, up from 21 percent), *Oil* (9 percent, up from 3 percent), and *Wind* (5 percent, again binding, up from 2 percent). The only technology to lose market share is *Gas* (a mere 1 percent, down from 18 percent). The rate of cost reduction would still attain 5.07 percent p.a. rather than 5.00 as in the actual portfolio, while risk declines to 2.03 from 3.10. One explanation of why *Gas* is almost phased out is its weak diversification effect, the correlation of its SURE residuals with *Coal* attaining 0.7605, the maximum value of Table 2. Therefore, current U.S. power

[12] Using portfolio theory for three U.S. generating technologies, Berger et al. (2003) also concluded that *Coal* dominates the MV portfolio with a share of 77 percent.

generation is inefficient from an investor point of view. It could be made more efficient by substituting *Gas* by *Coal*, *Nuclear*, *Oil* (not in the MER_C portfolio), and *Wind*.

If correlated shocks affecting generation costs would not have been taken into account (as in past studies), the results would have been very different, quite possibly misleading investors. Figures A1 and A2 in the Appendix display the OLS-based frontiers for the United States. Without constraints (Figure A1), the MER portfolio would have contained 100 percent *Coal*[13] (rather than 100 percent *Nuclear* as in the SURE-based case, see Figure 2). The MV alternative, on the other hand, would have called for a portfolio with 63 percent *Coal*, 27 percent *Nuclear*, and 10 percent *Wind*, quite different from the SURE-based solution that excludes *Wind* while allocating 56 percent (rather than 27 percent) to *Nuclear*. Moreover, investors would have little incentive to adjust their technology mix because OLS-based expected returns are at least 0.5 percentage points lower and volatilities are only slightly below the SURE-based estimates, regardless of whether or not feasibility constraints are imposed. With constraints imposed, however, OLS-based estimates would have resulted in efficient portfolios that practically coincide with the SURE-based ones (compare Figures A2 and 3). This was to be expected since most constraints are binding in both alternatives.

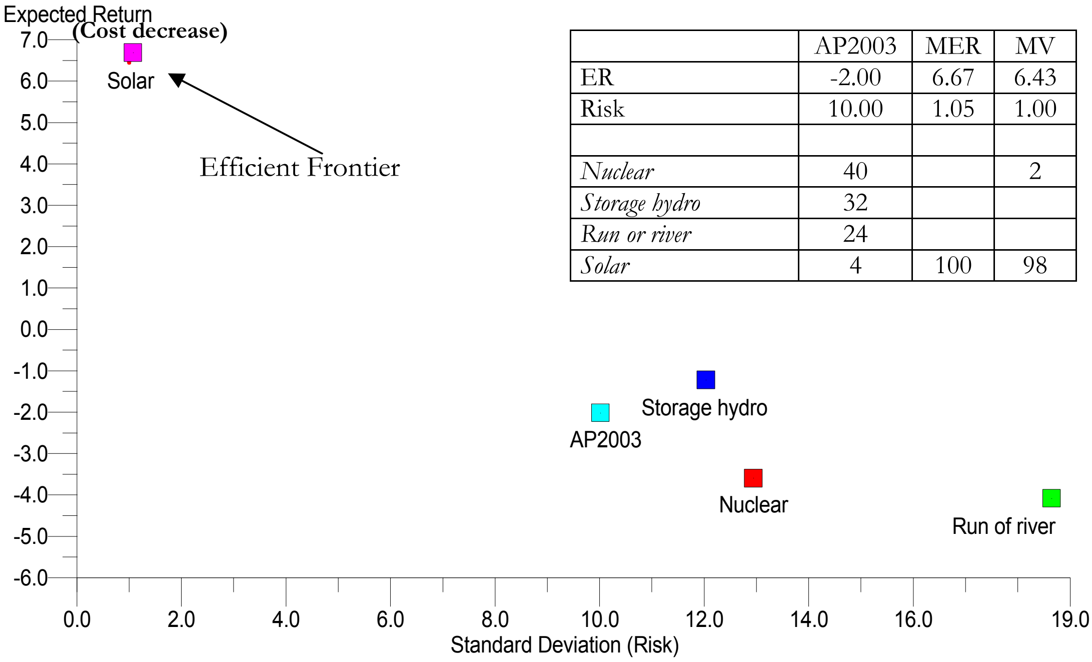
5.2.2 Current (2003) efficient electricity portfolios for Switzerland

Figure 4 displays the efficient electricity portfolios again (as of 2003) for Switzerland. Here, it is *Solar* rather than *Nuclear* (as in the United States) that dominates the MER portfolio with a 100 percent share. Opting for the MER portfolio, one would achieve a cost reduction of 6.67 percent p.a. (rather than the 2.00 percent p.a. cost increase with the actual portfolio), with volatility down from 10.00 to 1.05 percent p.a. The MV portfolio consists of 98 percent *Solar* and 2 percent *Nuclear*, expected return being 6.43 percent p.a. and risk, a mere 1.00. Clearly, in both countries non-CO_2 emitting technologies (*Nuclear* in the United States and *Solar* in Switzerland) play a dominant role in the unconstrained efficient portfolios.

However, shares of *Solar* close to 100 percent must be deemed unrealistic for Switzerland. Therefore, *Storage hydro*, *Run of river*, and *Solar* are constrained to their actual shares in 2003 (32, 24 and 4 percent p.a., respectively, see insert below Figure 5), leaving only *Nuclear* unconstrained. This can be justified by noting that *Storage hydro* and *Run of river* are already being utilized to full capacity (Laufer et al., 2004), while a share of *Solar* electricity of 4 percent constitutes the limit of what could have been achieved. The corresponding efficient frontier is shown in Figure 5.

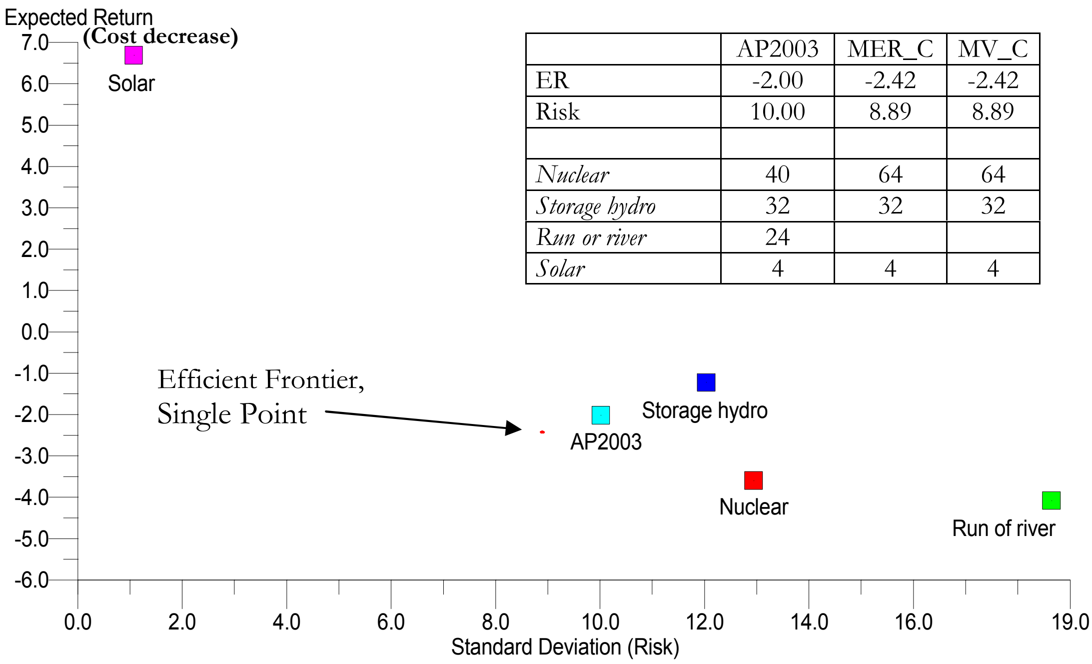
[13] Berger et. al. (2003), who do not control for correlation between unobserved shocks, also arrive at 100 percent *Coal*.

Figure 4: Efficient Electricity Portfolios for Switzerland
(2003, SURE-based, no constraints)



	AP2003	MER	MV
ER	-2.00	6.67	6.43
Risk	10.00	1.05	1.00
Nuclear	40		2
Storage hydro	32		
Run or river	24		
Solar	4	100	98

Figure 5: Efficient Electricity Portfolios for Switzerland
(2003, SURE-based, with constraints)



	AP2003	MER_C	MV_C
ER	-2.00	-2.42	-2.42
Risk	10.00	8.89	8.89
Nuclear	40	64	64
Storage hydro	32	32	32
Run or river	24		
Solar	4	4	4

Constraints imposed:
Storage hydro ≤ 32%, *Run of river* ≤ 24%, *Solar* ≤ 4%

The MER_C portfolio calls for a complete substitution of *Run of river* (actual share 24 percent) by *Nuclear* (64 percent), *Storage hydro* (32 percent, binding), and *Solar* (4 percent, binding). This surprising result is due to the fact that *Run of river* is highly correlated with *Storage hydro*, indicating that it has no diversification potential (see the correlation coefficient of 0.5054 in Table 3). At the same time, this technology has been subject to cost increases.

In all, Figure 5 suggests that if "realistic" constraints are respected, Swiss power generation could be made more efficient by allowing the share of *Nuclear* to substantially increase and abandoning *Run of river*. Generation cost would accelerate slightly, from 2.00 (actual) to 2.42 percent p.a., regardless of choice between MER and MV portfolios, but volatility would drop from 10.00 (actual) to 8.89.

Results based on OLS-estimated efficient frontiers are displayed in the Appendix (Figures A3 and A4). Acting on OLS-based estimates, investors would have expected marked cost decreases rather than the cost increases implied by SURE, at the same time severely underestimating volatility. Finally, they would have wrongly slashed the share of *Storage hydro* from 32 percent to 0 percent (MER_C) or 8 percent (MV_C), respectively. Therefore, the choice of statistical specification may again well matter for decision-making by utilities.

5.2.3 United States and Switzerland compared

This section is devoted to a comparison of results obtained for the two countries as of the year 2003, using SURE-based estimates. Starting with no constraints imposed (Figures 2 and 4), the United States could have achieved an average cost reduction of 5.76 p.a. by adopting the MER portfolio, Switzerland even 6.67 percent p.a. However, both countries would have had to completely change the composition of their portfolios, to 100 percent *Nuclear* (United States) and 100 percent *Solar* (Switzerland), respectively. Turning to the MV alternative, the volatility reduction achieved amounts to 1.54 percentage points (3.10 – 1.46) for the United States, much less than for Switzerland with its 9 percentage points (10.00 – 1.00). The implications in terms of portfolio composition are quite different for the two countries as well. Whereas opting for the MV alternative calls for 56 percent (rather than 100 percent) *Nuclear* in the case of the United States, it would leave *Solar* at almost 100 percent in the case of Switzerland.

Since shares close to 100 percent are far from reality in either country, constraints on admissible shares of technologies were imposed in Figures 3 and 5. This causes the existing amount of diversification to diminish in both countries, with *Coal* (United States) and *Nuclear* (Switzerland) becoming the principal energy sources. However, only the Swiss expected rate of return drops (from a 6.67 percent cost reduction to a 2.42 percent p.a. cost increase), associated with a marked surge in volatility.

On the whole, it appears that the U.S. electricity industry, while respecting feasibility constraints, would have gained by substituting *Gas* by *Coal*, *Nuclear*, and *Wind* technologies by 2003, regardless of the choice between the MER_C and the MV_ C portfolio. Swiss utilities would have stood to gain as well by adopting more *Nuclear* to the detriment of *Run of river*, an important source of primary energy until recently. Divergences of U.S. and Swiss investor's actual choices and efficient choices arose in past since generating technologies have been selected solely on an individual, case-per-case basis, failing to consider their contribution to overall portfolio performance.

Both industries at present fall short of their respective efficiency frontiers. In the United States, the gap amounts to a foregone 0.07 to 0.20 percentage points reduction of cost and 0.78 to 1.07 points volatility reduction (see Figure 3). In Switzerland, the estimates amount to a foregone 0.42 percentage points p.a. of cost and 1.11 points reduction of risk (see Figure 5). Therefore, there is some evidence suggesting that the more heavily regulated (Swiss) industry is characterized by a higher degree of inefficiency in the allocation of generating technologies than its largely deregulated U.S. counterpart.

6 Conclusions

The objective of this contribution was to apply portfolio theory to determine the current (2003) efficient frontiers for power generation in the United States (traditionally fossil-based) and Switzerland (traditionally hydro- and nuclear-based). The observation period covers 1982 to 2003 (United States) and 1986 to 2003 (Switzerland), respectively. Because the error terms proved to be correlated across equations, Seemingly Unrelated Regression Estimation (SURE) was adopted for estimating the covariance matrix used in determining efficient portfolios.

Interestingly, the maximum expected return (MER) portfolios of both countries boil down to one non-CO_2 energy source (*Nuclear* in the United States and *Solar* in Switzerland). When constraints limiting changes from the status quo are imposed to reflect the high cost associated with adjusting the technology mix, the MER_C portfolio for the United States contains 60 percent *Coal* (up from 56 percent) and for Switzerland, 64 percent *Nuclear* (up from 40 percent).

However, one could argue that for populations as risk-averse as the American and the Swiss (Szpiro, 1986), the minimum variance portfolio (MV) is appropriate. Adopting the MV criterion and imposing the same constraints, U.S. utilities would still want to assign 60 percent of their portfolio to *Coal*, almost entirely replacing *Gas*. The unit cost changes and hence returns of *Gas* are not only highly volatile but also strongly correlated with that of other technologies, depriving it of a possible diversification effect. At the same time, *Coal*-generated electricity became cleaner, causing (initially high) external costs to fall and making *Coal* very attractive from an investor point of view. In the Swiss MV_C portfolio, *Nuclear* accounts for even 64 percent while *Run of river* drops out (down from 24 percent). One is therefore led to conclude that both the current U.S. and Swiss technology mixes are inefficient even if "realistic" constraints are respected. While U.S. utilities are currently closer to their efficiency frontier than their more heavily regulated Swiss counterparts, they still may reap efficiency gains by investing more in *Coal* and moving away from *Gas*.

In contrast, efficiency frontiers estimated by OLS would tend to underestimate both expected returns and risk reduction potential in the case of the United States but overestimate achievable expected returns and underestimating risk reduction in the case of Switzerland. These discrepancies largely vanish, however, when feasibility constraints are imposed. Still, failure to account for correlation between unobserved shocks impinging on the different generation technologies using SURE does run the risk of opting for an inefficient solution. This finding contrasts with Berger et al. (2003), who concluded that the outcome of portfolio analysis is insensitive to econometric estimation techniques. However, the present study agrees with earlier ones in suggesting that utilities and policy makers, by adopting a single-technology approach, fail to take account of correlations between risky generating technologies. The consequence is a portfolio of generating technologies that is inefficient, achieving a too low expected rate of return and/or suffering from excessive volatility.

These statements are based on an investor view. To the extent that utilities are able to change their technology mix at low cost, the user view may be justified, emphasizing cost levels rather than cost changes over time. Future contributions therefore may compare the two views. They could also emphasize prediction rather than postdiction, examining whether emergent new technologies are part of future efficient frontiers. Finally, the strong assumption of a once-and-for-all decision regarding the choice of technology needs to be relaxed. A real options approach could be used to account for the irreversibility often inherent in the decision to adopt a technology. Deferring adoption may become the preferred choice in the face of stochastic cost changes caused e.g. by a liberalization of energy markets – or its failure to materialize as expected. Still, the present study provides first indications of where to go in the future in an attempt to reach the efficient mix of power-generating technologies in countries that are as diverse as e.g. the United States and Switzerland.

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Appendix

Table A1: Results of SURE regressions, Switzerland (1986-2003)

	$\bar{R}$	*St.D.*	*Const.*	R_{t-1}	R_{t-2}	R_{t-3}	R_{t-4}	*Trend*	*Obs*	R^2
Nuclear	3.6	12.9	0.04	-0.74***	-0.93***	-1.22***	-1.37***	-0.18***	9	0.74
Run of river	4.1	18.6	0.33	-0.70***				-0.20	9	0.51
Storage hydro	1.2	12.0	0.25	-0.72***				-0.02	9	0.22
Solar	-6.7	1.0	-0.34***	-0.73***	-0.56**	-0.61*	-0.55**	0.01***	9	0.63

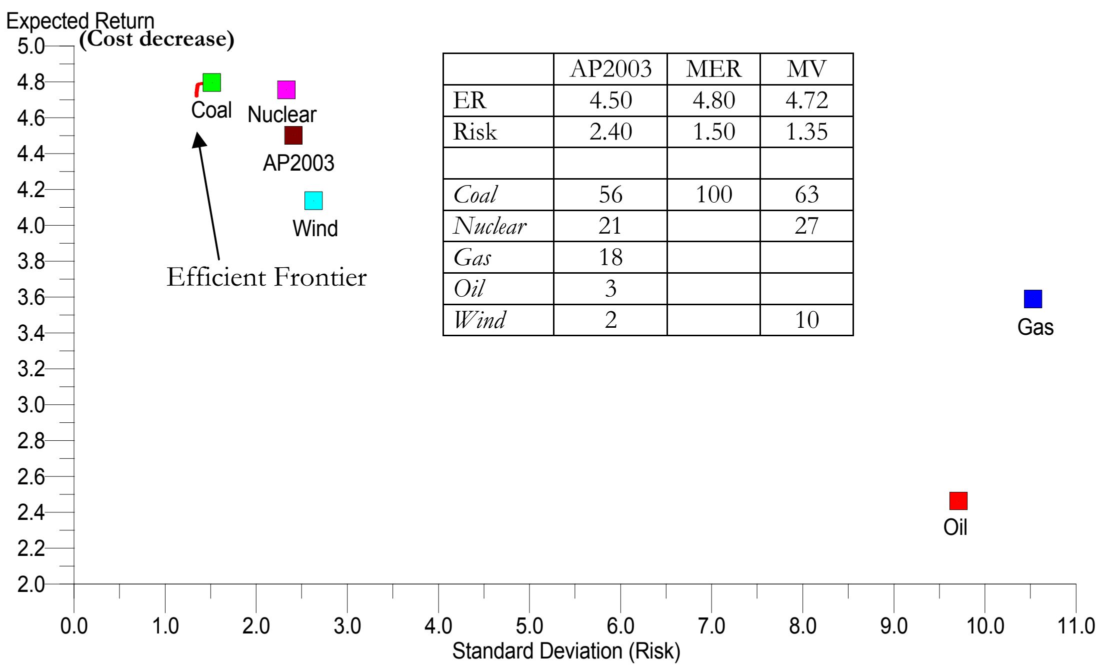
*** significant at 1 percent level, ** significant at 5 percent level, * significant at 10 percent level

Table A2: Results of OLS regressions, Switzerland (1986-2003)

	$\bar{R}$	*St.D.*	*Const.*	R_{t-1}	R_{t-2}	R_{t-3}	R_{t-4}	*Trend*	*Obs*	R^2
Nuclear	-4.3	2.2	-0.10*	-0.03	-0.29	-0.14	-0.38*	0.001	14	0.38
Run of river	1.6	1.6	0.11	-0.64**				-0.01	10	0.44
Storage hydro	0.8	9.1	0.20	-0.54				-0.01	10	0.35
Solar	-6.7	1.0	-0.32	-0.69	-0.60	-0.58	-0.40	0.01	9	0.64

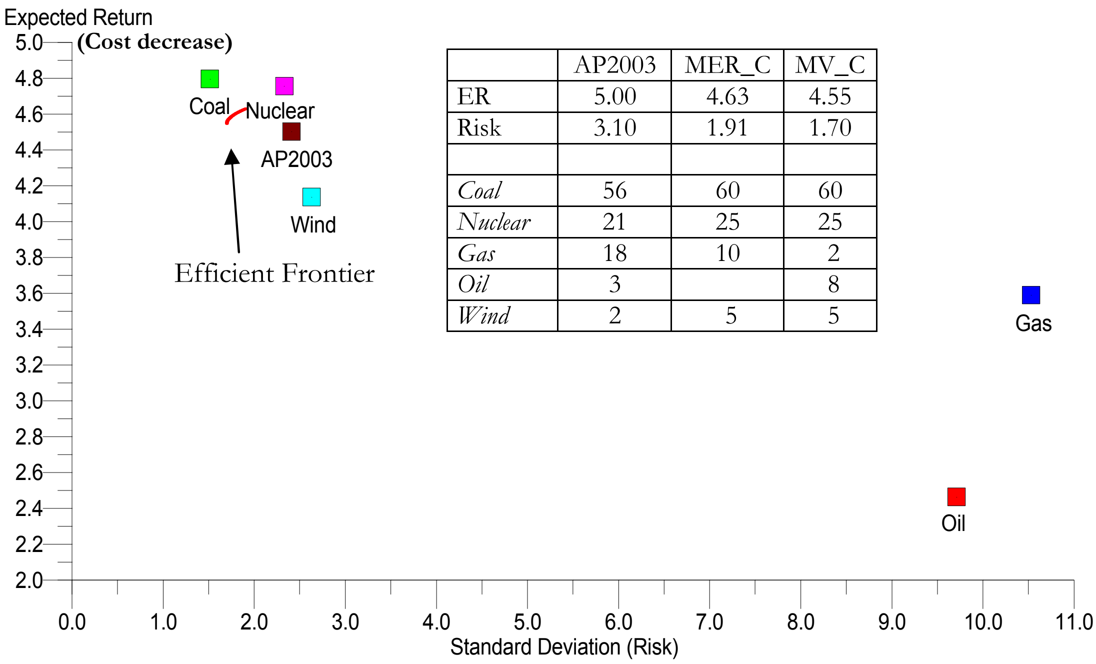
*** significant at 1 percent level, ** significant at 5 percent level, * significant at 10 percent level

Figure A1: Efficient Electricity Portfolios for the United States
(2003, OLS-based, no constraints)



	AP2003	MER	MV
ER	4.50	4.80	4.72
Risk	2.40	1.50	1.35
Coal	56	100	63
Nuclear	21		27
Gas	18		
Oil	3		
Wind	2		10

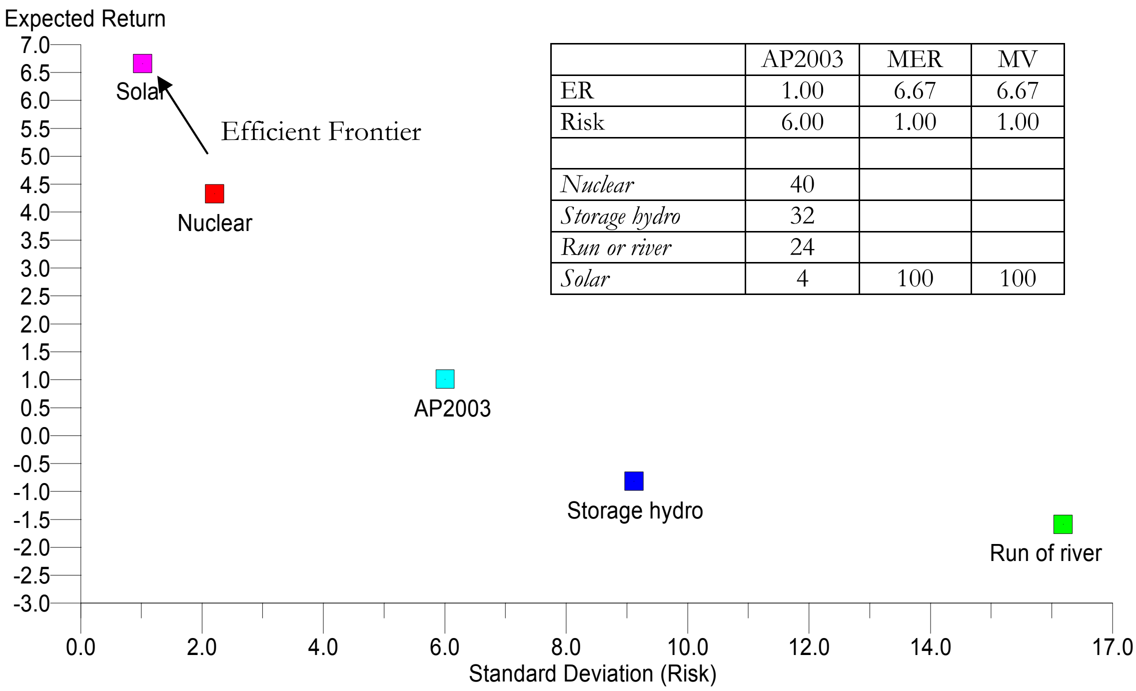
Figure A2: Efficient Electricity Portfolios for the United States
(2003, OLS-based, with constraints)



	AP2003	MER_C	MV_C
ER	5.00	4.63	4.55
Risk	3.10	1.91	1.70
Coal	56	60	60
Nuclear	21	25	25
Gas	18	10	2
Oil	3		8
Wind	2	5	5

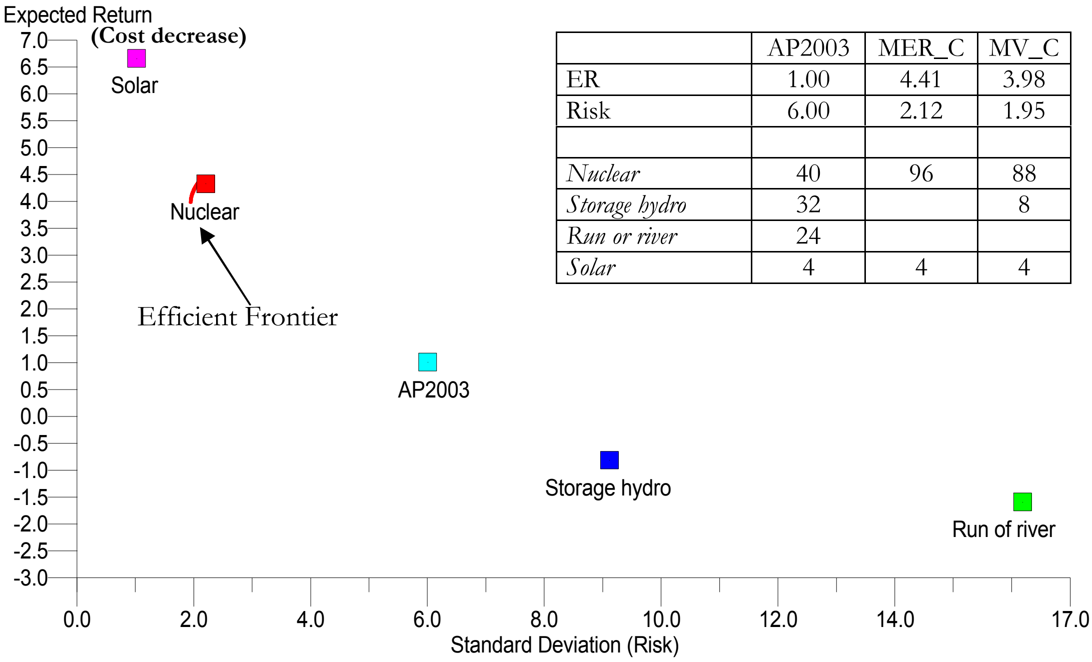
Constraints imposed:
Coal ≤ 60%, *Nuclear* ≤ 25%, *Oil* ≤ 10%, *Wind* ≤ 5%

Figure A3: Efficient Electricity Portfolios for Switzerland
(2003, OLS-based, no constraint)



	AP2003	MER	MV
ER	1.00	6.67	6.67
Risk	6.00	1.00	1.00
Nuclear	40		
Storage hydro	32		
Run or river	24		
Solar	4	100	100

Figure A4: Efficient Electricity Portfolios for Switzerland
(2003, OLS-based, with constraints)



	AP2003	MER_C	MV_C
ER	1.00	4.41	3.98
Risk	6.00	2.12	1.95
Nuclear	40	96	88
Storage hydro	32		8
Run or river	24		
Solar	4	4	4

Constraints imposed:
Storage hydro ≤ 32%, *Run of river* ≤ 24%, *Solar* ≤ 4%

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